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13. ABSTRACT ***(Maximum 200 Words)***
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WATER MIST IMPINGEMENT ONTO A HEATED SURFACE

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ABSTRACT

An experimental study on the interaction of a water mist with a heated surface is described. The long term objective is to produce experimental data that can be used to validate submodels for four key physical phenomena involved in the interaction of sprays with burning surfaces: (1) the effect of buoyancy (caused by the hot combustion products) on the trajectory of a single droplet, (2) the effect of evaporation on the trajectory of a single droplet, (3) the cessation of reaction and reduction in flame spread caused by the droplets on flaming surface combustion, and (4) the reduction in surface temperature caused by the effect of drop impingement, spreading, and evaporation, on surface combustion.

The short term objective was to complete experiments that mapped the size history of water droplets as they approached a hot surface using a Malvern Spray Analyzer to study the effect of both buoyancy and evaporation on droplet trajectory. Surface temperature profiles were recorded using fine-wire thermocouples. The influence of water mass flow rate and drop size distribution on the hot surface temperature profile is presented and discussed.

BACKGROUND

Interaction of water mists with fires have been studied for almost four decades (Braidech et al., 1995; Rasbash et al., 1960; Lugar, 1979; Mawhinney et al., 1994). However, there are no basic models that describe all interactions at this time. Braidech et al. (1955) have concluded correctly that, in most cases, the efficacy of a water spray is predominantly due to the oxygen displacement effect of the water evaporating, rather than thermal cooling. However, there are no detailed models describing the size reduction and evaporation of droplets in flames, or their effect on surface reaction kinetics. Indeed, even models that predict what size droplets will reach the surface are not available. The present work is aimed at providing experimental data that describe the interactions of water sprays with flaming and non-flaming surface combustion.

A recent study by Hicks and Senser (1995) shows that spray-target interactions can be described by dividing the process into a near-nozzle flow-development (NNFD) region and a target-interaction (TI) region. Key features of the NNFD region include spray formation, atomization, and entrainment of surrounding air. The TI region is characterized by two-way coupling between gas and liquid phase momenta where the spray can no longer be considered dilute, i.e. in the boundary layer near the target itself. Key features are deposition of some drops, depending on their sizes (big drops are more likely to impact the surface due to their larger momentum-to-aerodynamic drag ratio), and the formation and growth of a boundary layer which makes it difficult for drops to deposit as one moves further from the spray centerline. However, the flow physics studied are different for flames/heated surfaces than they are for unheated surfaces accurate, spatially resolved measurements of droplet sizes and velocities are necessary for submodel development.

Many studies have been performed that quantify the vaporization process of both single and multiple droplet arrays impacting on hot surfaces (DiMarzo and Evans, 1986, DiMarzo et al., 1989). These studies have also identified the need for spatial and temporally resolved data of the droplet trajectory as it approaches a hot surface (including buoyancy effects) as well as the temperature distribution of the surface material. The different components that describe both the droplet trajectory and the temperature distribution over the surface as a function of time will be studied in detail in this project by separating the various physical processes. This paper concentrates on one aspect.

EXPERIMENTAL APPARATUS

The experimental apparatus consists of the spray nozzle and its associated feed systems, the heated surface and its associated power supply, a Malvern Spray Analyzer to measure near-plate water mist droplet size distributions, and fine-wire

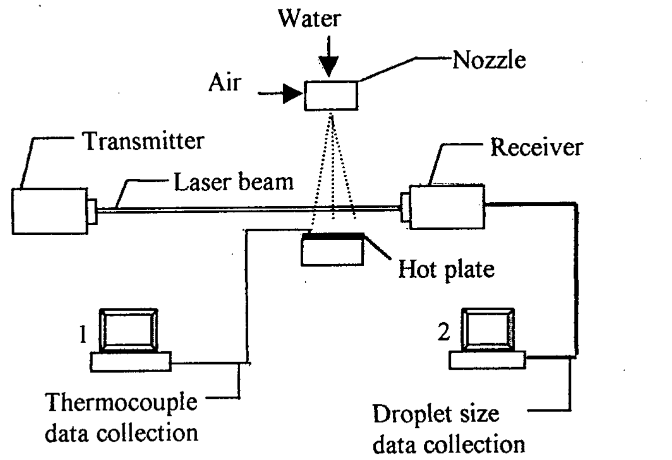

Figure 1 The schematic diagram of experimental apparatus.

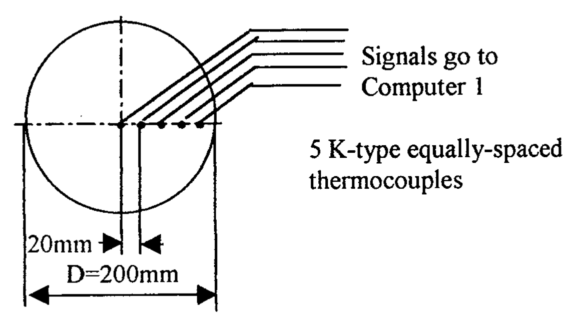

Figure 2 The structure of the heated surface with the thermocouples.

type-K thermocouples connected to a computer to record transient temperature distribution on the heated surface. Thermocouple voltage signals are transferred to the computer using an amplifier. All items are summarized below. Figure 1 and 2 are the detailed schematics.

The spray nozzle is an effervescent design, and was originally used by Lund et al. (1993). The operation principle is that of a metered flowrate of air injected into a known flowrate of liquid such that bubbles are formed inside the nozzle body. The resulting two-phase flow exits the final orifice in an annular configuration. The rapidly moving air core causes the slower moving liquid annulus to break up into ligaments, with the ligaments then breaking up into drops.

The heated surface is a 20cm diameter, 5mm thick copper plate located 25cm beneath the nozzle. It is placed on a spiral wound resistance heater whose power is supplied by a pair of Variacs and a transformer.

A Malvern model 2600 Spray analyzer was used to obtain all drop size data. The Malvern instrument operates on the principle of Fraunhofer diffraction. It operates by collecting light diffracted by particles in the medium, through use of a Fourier transform lens, and focusing it on a planar detector array. The detector array consists of thirty concentric semicircular elements of varying area. Each element is a photodiode that converts incident light energy into a proportional current. The currents are transformed to voltages that are sampled and stored by a dedicated microcomputer. After storage, the microcomputer iteratively determines a particle size distribution that would yield the diffracted light profile as measured by the detector array. Optical effects, which results in sampling errors must be considered when extending the Malvern sizer to media with time varying index of refraction gradient. In our experiments, some beam steering was expected because the index of refraction gradient of air in the measuring volume was influenced by the heated surface below. However, spurious signals were removed by "killing" data on the innermost detector elements, as suggested by Dodge and Cerwin (1984) and the manufacturer. The Malvern Spray Analyzer calibration was checked using the procedure specified by Dodge (1984).

RESULTS AND DISCUSSION

The baseline temperature distribution on the copper plate in the absence of a spray was quite uniform, as Table 1 shows. By changing the spray mass flow rate and initial drop size distribution, their influence was investigated as presented below.

Table 1: Average temperature distribution of the copper plate before spray

	Temperature (°C)
r=0 mm	596.5
r=20 mm	601.3
r=40 mm	601.8
r=60 mm	605.8
r=80mm	602.4
Average Temp.(°C)	601.6
Standard deviation(°C)	3.0

Note: The expected thermocouple system accuracy is ±2.2°C; 32 samples are collected at each radial location at frequency f=1000Hz.

(a) Influence of water mass flowrate

By applying sprays of D_{32}=100 μm (obtained though adjusting the flow rates of water and air simultaneously), the influence of water mass flow rate was investigated. The mass flow rates used in this experiment were 0.214, 0.323, 0.480, 0.609, 0.742 and 0.923 g/s, respectively. Table 2 and Figure 3 shows the temperature distributions at t=8 s (this instant was chosen since for the case of m=0.923 g/s, the temperature of the center point was nearly at the boiling point; and after this instant, there was some water deposition on the plate, which is beyond our interest of study).

Figure 3 shows that flow rate has a significant influence on the temperature profiles, especially in the center. This is because of the cone spray structure, which concentrates a large part of the mass flow along the spray axis. The larger the flow rate, the more rapidly the temperature decreases, since more

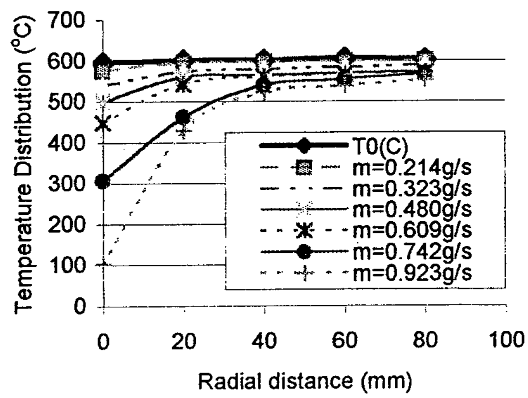

Figure 3 Temperature distributions at t=8s for different flow rate. D_{32}= 100 μm sprays.

Table 2. Temperature Distribution at t=8 s

Radial distance (mm) / Flow rate (g/s)	0	20	40	60	80
0	596.5	601.3	601.8	605.8	602.4
0.214	575.9	596.1	598.3	598.8	600.6
0.323	540.2	573.3	579.6	584.1	589.7
0.480	500.7	560.6	564.8	589.7	573.2
0.609	449.7	543.3	560.9	566.8	571.7
0.742	306.3	463.0	540.0	555.0	568.0
0.923	102.5	430.0	522.0	538.0	553.0

energy is required to vaporize the droplets. For the largest flow rate, m=0.923 g/s, when t=8 s, the center temperature was very close to the boiling point of water. A small area of water deposition on the plate was observed quite soon after this. For m=0.742g/s, this situation occurred much later at about t=120 s. For other cases, droplets were visually observed bouncing from the plate and vanished rapidly, with the final equilibrium states reached after different periods of time.

Figure 4 shows the time history of the temperature distribution for the case of m=0.742 g/s. It should be pointed out that because there were radiation, convection and conduction heat losses at the same time, it is difficult to tell accurately what percent of energy was consumed by evaporation at this time.

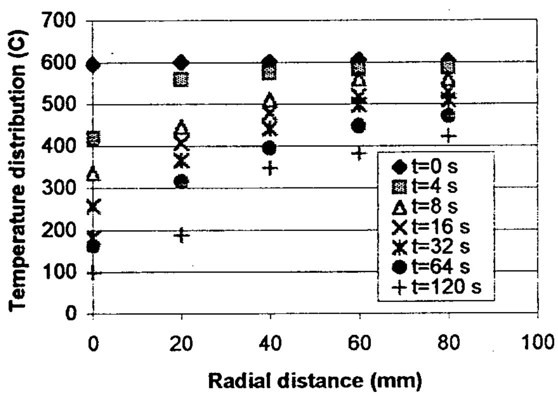

Figure 4. The time history of temperature profile for m=0.742 g/s.

(b) Influence of droplet size distribution

Three mean drop sizes were used to investigate the influence of droplet size distribution on the temperature profile, all at the flow rate of 0.923g/s. Sizes used here are D_{32}=70, 100 and 200 μm. Detailed information is provided in Figure 5.

From this figure, we see that for the same flow rate, the smaller drop size spray exhibits temperature difference between the plate center line and edge. When small droplets approach the heated surface, they evaporate rapidly and consume more energy, while for large droplets, energy is mainly consumed after they impact the plate, disintegrate into small droplets, bounce (because of their high speed), and finally evaporate.

(c) Influence of evaporation and buoyancy on near-plate spray size distribution

Measurements of spray size distribution when they approach the hot plate were obtained at a height of 40 mm

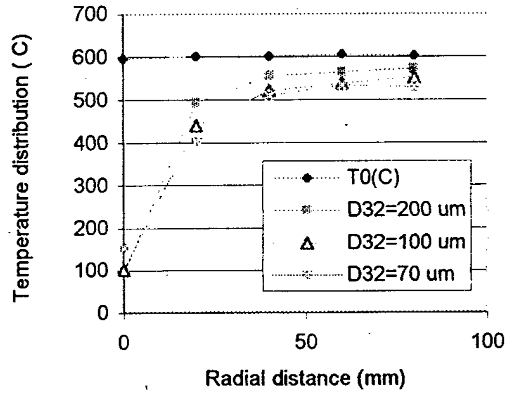

Figure 5. Temperature distribution at m=0.923 g/s, t=8 s for sprays having D_{32}=70, 100 and 200 μm.

above the plate. Measurements could not be made closer to the plate because the temperature of the air just above the surface was very high, thus the index of the reflection would be seriously influenced and too much beam steering would be present. Table 3 gives a preliminary indication of the size distribution near the plate:

Table 3: Near-plate spray size distribution at t=1 s

Original size: D_{32}=100 μm

Mass flow rate (g/s)	Average size (μm)
0.214	158
0.323	175
0.480	180
0.609	188
0.742	184
0.923	176

From the table we see that , the average size measured increases as the flow rate increases, reaches its maximum at m=0.609 g/s, then decreases. One possible reason for the observed behavior is that the proportions of small and large drops are nearly the same for all sprays. Here we have constant heat supply. In the low flow rate case, small drops vanish rapidly, and large drops have partly evaporated. As the flow rates increases, the number of small droplets increases, the portion of energy used to evaporate the small drops becomes greater and greater, thus D_{32} of the spray increases. When the flow rate is quite large, there is not enough energy to evaporate all the small drops during the short time between the droplets exit the nozzle and impact on the plate, thus the D_{32} decreases again. Further modeling should help resolve this issue.

The influence of buoyancy on droplet size distribution may be considered as follows: (1) Buoyancy increases the time between when the droplets exit the nozzle and reach the heated plate, hence increases the evaporation. (2) The rising air stream enhanced the interaction and heat transfer between the droplets and the ambient air, thus indirectly enhancing evaporation rate. Therefore, for small flow rates, since buoyancy has more significant influence on small droplets (decelerating their velocities much faster), the small droplets' evaporation rate and the evaporated portion both increase. This contributes to increasing D32. For the larger flow rates, buoyancy decreases D32 for the same reason. In both cases, buoyancy narrows the size distribution. However, the influence of buoyancy on droplet size distribution is much less than evaporation.

SUMMARY

The effect of both evaporation and buoyancy on droplet size history and the corresponding temperature distribution on a hot surface at 600°C are described. The influence of water mass flow rate and drop size distribution on the hot surface temperature profiles is presented and discussed. Experiments investigating the separate effects of buoyancy and evaporation using monodisperse spray will be carried out in the near future.

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REFERENCES

Braidech, M.M., Neale, J.A., Matson, A.F., And Dufour, R.R. (1955), "The mechanism of extinguishment of fire by finely divided water", Underwirters Laboratories Inc. for the National Board of Fire Underwirters, NY, p.73

Di Marzo, M., Kavoosi, and Klassen, M. (1989), "Transient cooling of a hot surface by droplets evaporation", *Report prepared for the National Institute of Standards and Technology, NIST-GCR-89-559*, University of Maryland, College Park, MD.

DiMarzo, M., and Evans, D. D., (1986) "Evaporation of water droplet deposited on a hot high thermal conductivity solid surface", *National Bureau of Standards Interagency/Internal Report, NBSIR* 86-3384.

Dodge, L. G. (1984), "Calibration of the Malvern Particle Sizer", *Applied Optics*, vol. 23, pp. 2415-2419.

Dodge, L. G. and Cerwin (1984), *ASTM STP 848* (Ed. J. Tishkoff, R.D. Ingebo, and J.M. Kennedy).

Hicks, P. G., and Senser, D. W. (1995), *J. of Fluids Engg.*, vol. 117, pp. 713-719.

Lugar, J.R., (1979), "Preliminary test results of fine water mist fire protection systems study", David W. Taylor Navel Ship R&D Center, Maryland.

Mawhinney, J.R., Dlugogorski, B.Z., and Kim, A. K. (1994), *Proceedings of the Fourth International Symposium on Fire Safety Science*, (Ed. T. Kashiwagi), Ottawa, CA, pp47-60.

Rasbash, D.J., Rogowshi, Z.W., and Stark, G. W.V.(1960), *Combust. Flame*, vol. 4, pp223-234.